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Soil organic carbon in the rocky desert of northern Negev (Israel)

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Abstract

Purpose So far, the soil organic carbon (SOC) literature is dominated by studies in the humid environments with huge stocks of vulnerable carbon. Limited attention has been given to dryland ecosystems despite being often considered to be highly sensitive to environmental change. Thus, there is insufficient research about the spatial patterns of SOC stocks and the interaction between soil depth, ecohydrology, geomorphic processes, and SOC stocks. This study aimed at identifying the relationship between surface characteristics, vegetation coverage, SOC, and SOC stocks in the arid northern Negev in Israel.

Materials and methods The study site Sede Boker is ideally suited because of well-researched but variable ecohydrology. For this purpose, we sampled five slope sections with different ecohydrologic characteristics (e.g., soil and vegetation) and calculate SOC stocks. To identify controlling factors of SOC stocks on rocky desert slopes, we compared soil properties, vegetation coverage, SOC concentration, and stocks between the five ecohydrologic units.

Results and discussion The results show that in Sede Boker, rocky desert slopes represent a significant SOC pool with a mean SOC stock of 0.58 kg C m^{-2} averaged over the entire study area. The spatial variability of the soil coverage represents a strong control on SOC stocks, which varies between zero in uncovered areas and 1.54 kg C m^{-2} on average in the soil-covered areas. Aspect-driven changes of solar radiation and thus of water availability are the dominant control of vegetation coverage and SOC stock in the study area.

Conclusions The data indicate that dryland soils contain a significant amount of SOC. The SOC varies between the ecohydrologic units, which reflect (1) aspect-driven differences, (2) microscale topography, (3) soil formation, and (4) vegetation coverage, which are of greatest importance for estimating SOC stocks in drylands.

Keywords Drylands · Ecohydrology · Rocky deserts · SOC stock · Soil organic carbon · Topography

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1 Introduction

1.1 Soil organic carbon and the global carbon cycle

The global soil system is the largest terrestrial reservoir of organic carbon, which stores approximately 2,400 Pg ($Pg=10^{15}$ g) of soil organic carbon (SOC) in the top 2 m (Amundson 2001; Kirschbaum 2000). Soil and climate systems are closely coupled through the exchange of C between the atmosphere, biosphere, and pedosphere (Berhe et al. 2008). Therefore, there has been increasing international interest in the ability of soils to affect atmospheric concentrations of carbon dioxide (CO_2) (Houghton 2007; Mishra et al. 2009; Sarmiento and Gruber 2002; Schlesinger 1977, 1990; Wigley and Schimel 2005). The risk of global warming and the potential to use soils as a carbon sink in the context of the Kyoto Protocol have increased the attention of the scientific community to SOC stocks and fluxes in terrestrial ecosystems, especially in regions sensitive to climatic change (Branchu et al. 1993; IPCC 2007; Mishra et al. 2009; Smith and Heath 2002). However, the size and dynamics of the global SOC pool are still not well known (IPCC 2007; Quinton et al. 2010; Seip 2001). Precise measurements and estimates of the spatial distribution of SOC stocks are necessary to quantify the SOC sink or source capacity of soils in changing environments. The spatial variation of SOC is significantly influenced by environmental factors such as climate, topography, soil and bedrock materials, vegetation, disturbance, and surface processes due to human activity (Tan et al. 2004).

1.2 Carbon stocks in drylands

Even though drylands occupy 47.2 % of the earth's land surface, their importance in the global carbon cycle received limited attention (Asner et al. 2003; Schimel 2010). Global dryland soils contain 15.5 % of the world's total SOC to 1 m depth (IPCC 2007; Lal 2003; Lal et al. 2001; Schimel et al. 2000). This is about 40 times more than what was added during the 1990s into the atmosphere through anthropogenic activities, estimated at 6.3 Pg C year^{-1} (IPCC 2007; Lal 2003; Lal et al. 2001; Schimel et al. 1994, 2000). Dryland ecosystems are often regarded as “hot spots” of climate change, with large, rapid, and variable responses to even the smallest changes of climate conditions (Farage et al. 2003; Lal 2003; Yair 1990). Furthermore, dryland soils are prone to degradation and desertification due to human activities. Consequently, the majority of degraded dryland soils can be considered as far from SOC saturation, suggesting a high potential of SOC uptake (Farage et al. 2003; Lal 2003). Additionally, recent results (Rotenberg and Yakir 2010) show that dryland forests in Israel take up carbon at rates similar to forests in more humid continental Europe. Based on these results, they suggest that 1 Pg out of 3.2 Pg generating the annual increase in atmospheric concentration of CO_2 can be sequestered by reforestation of dryland soils. In contrast to soils from humid regions, dryland soil areas are less likely to lose SOC because the lack of water limits SOC mineralization and therefore the flux of SOC into the atmosphere. Consequently, the residence time of SOC in desert soils can be much longer than in soils of humid regions (Glenn et al. 1993), and the ratio of the soil to living biomass SOC pool might be greater in drylands than in tropical forests (Farage et al. 2003; Lal 2009; Lal et al. 2001).

1.3 SOC-stock calculation and links to soil-forming factors

SOC stocks (kg C m^{-2}) are generally calculated based on the mean soil organic carbon contents SOC_c (g 100 g^{-1}) of the fine soil fraction (<2 mm), the mean bulk density BD (in grams per cubic centimeter), the mean mass ratio of coarse soil fragments (>2 mm) CF_i (g 100 g^{-1}), and the soil thickness d_{soil} (centimeters):

$$SOC_{stock} = 0.1 \times d_{soil} \times BD \times SOC_c \times (1 - CF/100) \quad (1)$$

In humid environments, which are characterized by strong agricultural activity, human-controlled land cover generally exerts a strong variability on SOC concentration that in turn dominates the spatial variability of SOC stock (Goidts and van Wesemael 2007; Grieve 2001; Lal 2005; Leifeld et al. 2005; van Wesemael et al. 2010). In arid environments, however, the link between SOC stocks and soil-forming factors (such as climate, vegetation, and bedrock material) is much more complex than in humid agricultural landscapes. Significant diurnal temperature changes and the water deficit result in high physical and low chemical weathering rates (FAO 2004). The strong disintegration of rocks and the low chemical transformation therefore suggest a strong control of properties of the parent material (e.g., given by soil thickness, BD, and CF in Eq. (1)) on SOC stocks. Parent material in arid environments is often transported during severe soil erosion caused by extreme precipitation events (Yair 1990). Wash processes, however, are not continuous but disconnected, and sediment is generally transported only over short distances due to the disconnectivity of overland flows (Michaelides and Chappell 2009; Yair 1992). Thus soils, especially in arid environments, need to be “considered as mobile systems, which has major consequences for terrestrial biogeochemical cycles” (Quinton et al. 2010). Furthermore, arid environments lack a continuous vegetation coverage but are dominated by shrub vegetation that concentrates the biogeochemical activity in “islands of fertility” (Schlesinger and Pilmanis 1998; Schlesinger et al. 1996). Therefore, the shift from continuous grassland to patchy shrub vegetation with increasing aridity introduces a further element of complexity in the distribution of SOC stocks.

1.4 Estimation of dryland SOC stocks

Due to continuous runoff under humid conditions, SOC stocks are generally related to the surface morphology, which controls processes such as erosion and deposition and thus SOC fluxes and sequestration (Egli et al. 2009; Griffiths et al. 2009; Rosenbloom et al. 2006; Tan et al. 2004; Yoo et al. 2006). Topographic parameters, such as slope (Berhe et al. 2008; Tsui et al. 2004), curvature (Rosenbloom et al. 2006; Yoo et al. 2006), and relief position (Glatzel and Sommer 2005), have been shown to correlate with SOC stock under humid conditions. In contrast to humid environments with well-developed soils, arid environments with shallow soils are characterized by a lack of connectivity in runoff causing in turn an exceedingly high spatial variability of soil depth (Laity 2008; Parsons and Abrahams 2009; Yair 1990;

Yair and Danin 1980). Since runoff exerts a strong control over water availability, soil formation, and soil erosion and deposition, simple relationships of topographic parameters (such as slope, curvature, and wetness index) and soil properties and SOC stocks are not expected in arid environments.

Vegetation needs to be considered as a major factor controlling SOC stocks in arid environments (FAO 2004; Zhou et al. 2011). First, strong variations of soil moisture availability cause a patchy vegetation distribution, which in turn may exert a strong control on carbon stocks (Olsvig-Whittaker et al. 1983; Schlesinger et al. 1996). Second, in contrast to humid environments, which are characterized by high net primary production (NPP) and increased organic matter mineralization, dry environments have lower NPP, but also lower decomposition rates (Lal 2009; Schlesinger 1991). Third, while high temperatures favor high CO_2 efflux, low decomposition rates (due to water deficit) limit vegetation-driven carbon sequestration in hot arid climates (Fang and Moncrieff 2001; Farage et al. 2003; Qi et al. 2002) and thus may limit the impact of vegetation on SOC stocks. Thus, the link between soil moisture, vegetation coverage, and soil properties to SOC stocks and their relative importance for the spatial patterns of SOC stock in arid environments are much less clear than under humid conditions.

The spatial variability of relevant soil properties (Eq. (1)) presents a major challenge to the establishment of SOC stocks in arid and semi-arid environments. Despite the apparent significance of the dryland SOC pool, systematic studies on the spatial variability and the effects of environmental factors (such as soil moisture and vegetation coverage) in rocky desert soils are still missing. Thus, there is a strong need to estimate SOC stocks in arid soils and to evaluate their importance under a changing climate (Rotenberg and Yakir 2010; Schimel 2010). This need provides the major motivation of our study, which aims (1) to determine SOC stocks in a range of ecohydrologically different slope environments, (2) to identify soil properties relevant for the SOC stocks in each ecohydrologic setting, and (3) to assess the effects of NPP (represented by vegetation coverage) on SOC stocks.

The study was conducted in the northern highlands of the Negev desert in Israel near the town of Sede Boker, which is ideally suited because of well-researched ecohydrology. The influence of surface properties and patches of rock and soil on ecohydrology and vegetation has been intensely investigated in this area (e.g., Evenari et al. 1980; Olsvig-Whittaker et al. 1983; Yair 1990; Yair and Danin 1980). Based on this research, it was possible to determine SOC stocks in a range of ecohydrologically different slope environments and to identify soil properties relevant for SOC concentration and stock. The established link between vegetation coverage and water supply at Sede Boker also offers the opportunity to test the effects of ecohydrology on SOC, especially the balance between NPP (indicated by vegetation coverage) and SOC-stock development.

2 Study site

The Sede Boker research area is located in a second-order drainage basin (4.5 ha) about 40 km south of Beersheva (30° 52′ N, 34°48′ E) in the northern Negev Desert of Israel (Fig. 1). The elevation ranges between 485 and 535 m above sea level. The mean annual air temperature in Sede Boker is 20 °C (Dan et al. 1972), and mean monthly temperatures vary from 9 °C in January to 25 °C in August. The average annual rainfall, observed during a 30-year period (Yair 1994), ranges from 34 to 167 mm, with an average of 91 mm (Kuhn and Yair 2004). Rainfall is concentrated during the winter season between October and April. Potential evaporation rates are approximately 2,500 mm, generating an arid climate (Evenari et al. 1980; Olsvig-Whittaker et al. 1983; Yair and Danin 1980).

The Upper Cretaceous bedrock stratigraphy is composed of three limestone formations that are the Netser, Shivta, and Drorim formation (Fig. 2). Based on Yair and Danin (1980), Olsvig-Whittaker et al. (1983), and Schreiber et al. (1995), the formations can be classified in four meso-scale surface structural units (Upper Netser, Lower Netser/Upper Shivta, Lower Shivta, colluvium above Drorim). The upper part of the slope is characterized by the Upper Netser formation with thinly bedded limestones and flint concretions. The lower part of the Netser and the Upper Shivta formation is a thinly bedded and densely fissured formation and could be considered as one structural unit according to Olsvig-Whittaker et al. (1983). The Lower Shivta formation is a massive unit with a low density of deep cracks. The Drorim formation represents the lowest unit, which is densely jointed and covered with an extensive colluvial mantle (Yair and Shachak 1982) (see Fig. 2). These bedrock formations provide distinctive surface properties influencing hydrology, plant communities, and therefore potentially the spatial distribution of SOC concentration and SOC stock.

In situ chemical weathering of bedrock is of minor importance for soil formation. Most of the substrate is not derived from the local limestone, but composed of aeolian loess-like sediments, which were deposited since the early Quaternary (Bruins 1986; Reifenberg 1947; Yaalon and Dan 1974). Based on the World Reference Base for Soil Resources (IUSS Working Group WRB 2006), the soil is dominantly classified as a desert brown Lithosol (Arkin and Braun 1965; Dan et al. 1972) with patchy and thin soil cover. Generally, the study area is characterized by three soil bedding types: (1) soil patches, which are mainly located at the base of rock steps, (2) soil material filling crevices

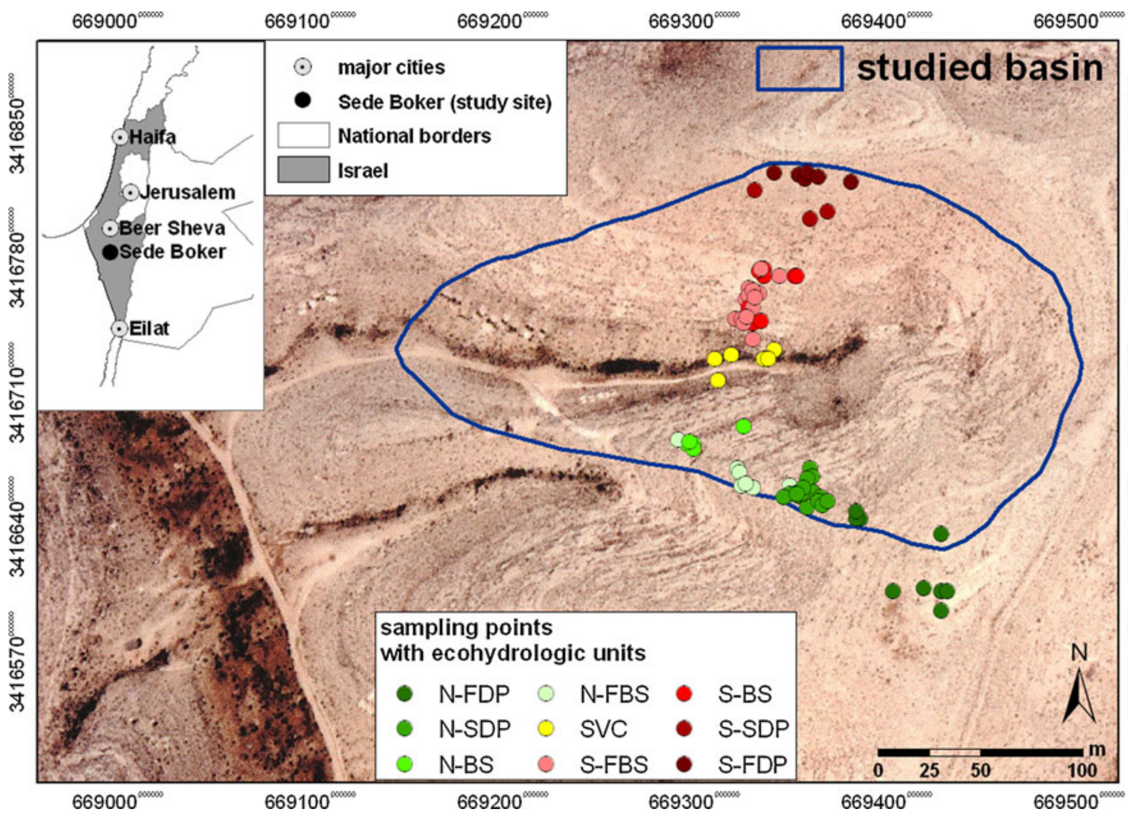


Fig. 1 Location of the study site and sampling points with respect to aspect and ecohydrologic units. *N* and *S* indicated northern and southern aspects, respectively. *FDP* flat desert pavement, *SDP* gently sloped desert pavement, *FBS* stepped and fissured bedrock slope, *BS* non-fissured bedrock slope, *SVC* slope and valley colluvium. Coordinates are given by projection system UTM longitude zone 36, latitude zone R, ellipsoid WGS 84

and fissures generated by rock shattering, and (3) colluvial soil sheets on bedding planes of the near surface rock strata. The loessic substrate is high in sand and silt (85–95 %), while clay content varies between 14.5 % in joints and crevices and 7–10 % in soil patches covering bedding planes (Olsvig-Whittaker et al. 1983; Yair and Danin 1980). Due to the arid conditions, with low vegetation coverage and high wind speeds and surface runoff, the soil genesis is

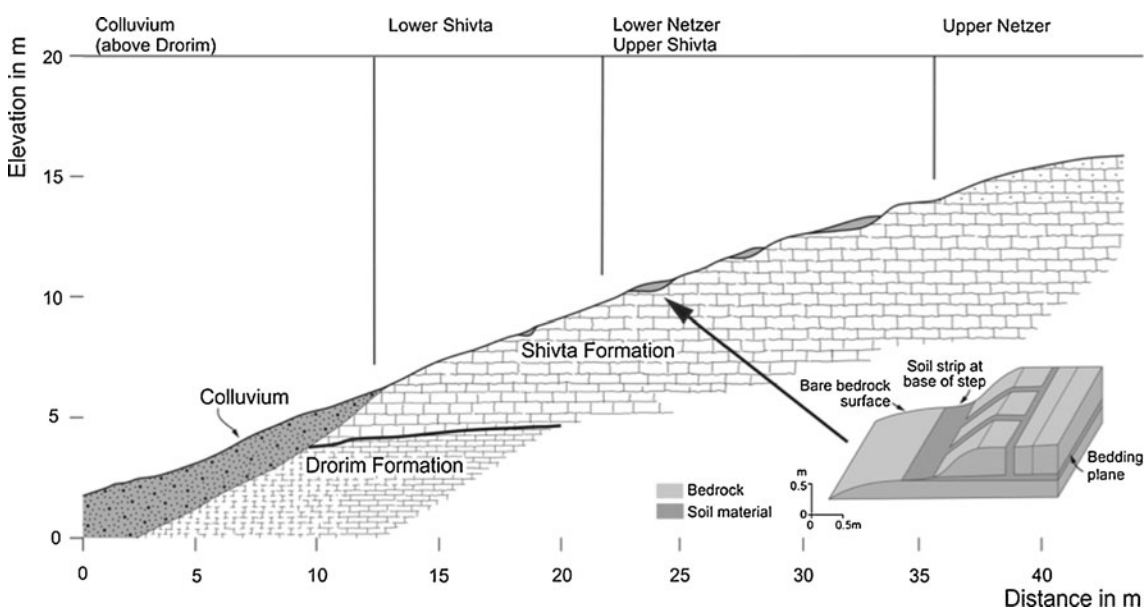


Fig. 2 Geological cross section with lithological formations of the study site modified after Olsvig-Whittaker et al. (1983)

strongly controlled by the erosion and deposition caused by wind and surface runoff (Olsvig-Whittaker et al. 1983).

Despite the meteorologic aridity, the vegetation of this region is considered to be at the transition of the Irano-Turanian plant geographical region and the Saharo-Arabian region with some Mediterranean components (Danin et al. 1975; Olsvig-Whittaker et al. 1983; Yair and Danin 1980; Yair and Shachak 1982; Zohary 1962). The study area has a range of communities from semi-desert (10–30 % perennial shrubs and semi-shrubs) on the rocky upper north exposed slopes, which are characterized by an unfavorable water regime (Yair and Danin 1980), to some patches of true desert vegetation (less than 10 % perennial cover) on the lower colluvium and southerly exposed slopes. The most favorable water regime prevails in soil pockets and crevices; therefore, vegetation is more or less concentrated along the soil patches and bedrock joints filled with soil. Hence, the study site is very well suited to determine the role of surface ecohydrology for SOC stocks.

3 Methods

Based on the aims of the study, the following objectives for field sampling and data analysis are derived: (1) to sample slope sections with different ecohydrologic characteristics (soil and vegetation) to calculate SOC stocks; (2) to compare soil properties, vegetation, SOC concentrations, and SOC stocks for the different ecohydrologic units; and (3) to identify the factors which determine SOC stocks on rocky desert slopes.

3.1 Ecohydrologic units along rocky desert slopes at Sede Boker

The study site was mapped based on differences in surface conditions (such as geology, rock/soil ratio, soil distribution, soil bedding, soil depth), microclimate (as indicated by slope gradient and aspect), and vegetation according to Olsvig-Whittaker et al. (1983), Schreiber et al. (1995), and Yair and Raz-Yassif (2004). These factors control the water availability for vegetation and thus determine the ecohydrologic units (EHUs) along the rocky desert slopes. The following units were distinguished for soil sampling and vegetation mapping (Table 1): (1) flat desert pavement (FDP), (2) gently sloped desert pavement (SDP), (3) non-fissured bedrock slope (BS), (4) stepped and fissured bedrock slope (FBS), and (5) slope and valley colluvium (SVC). A detailed description of each unit is given in Table 1. The FDP represents the uppermost unit in the study site, which represents the flat plateau in which the basin is incised. It is characterized by a medium soil and vegetation coverage (~30 %). The SDP forms the transition from the FDP to the incised valley. It has a higher soil and vegetation coverage, which is conditioned through the accumulation of aeolian deposits. The bedrock slope, which is located below the SDP, is subdivided into stepped fissured (FBS) and non-fissured bedrock (BS). The FBS shows a characteristic stepped topography with a localized soil cover in small soil pockets and noncontinuous soil strips. The former forms in zones of structural weakness in the Shivta formation and the latter are deposits of fine sediment at the base of the bedrock step below the soil pockets (Yair and Shachak 1982). The vegetation coverage in this unit is generally high. The BS is a massive unit of bedrock with a low density of deep cracks. Soil cover in this unit is generally very shallow and covers only 5–10 %. The colluvium, at the base of the slope, can be distinguished in slope colluvium and valley colluvium (SVC). This unit is characterized by a continuous deposition of colluvial sediments, which provide the parent material for the formation of soil. However, soil coverage is still limited due to the presence of large rocks, which cover a significant portion of the surface and inhibit the growth of vegetation and soil formation.

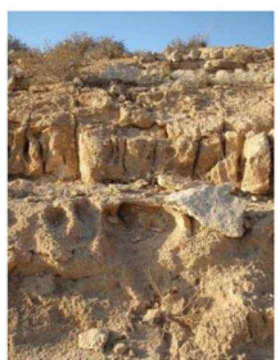
The ecohydrology of these units is strongly influenced by their surface characteristics. Therefore, the soil coverage was classified for each ecohydrologic unit using six soil-cover classes (I: <1 %; II: 1–2 %; III: 2–5 %; IV: 5–10 %; V: 10–30 %; and VI: >30 %) in the field (compare AG Bodenkunde 2005) and by visual interpretation of photos taken normal to the surface. Rocks larger than 20 cm, which cover the surface and prevent the growth of vegetation, were considered as "bedrock" and were excluded from soil coverage.

Vegetation was mapped and estimated for each ecohydrological unit based on the Braun-Blanquet (McAuliffe 1990) method as well as the plant guide of Zohary (1962) (see Table 1). The vegetation coverage was calculated on total surface (including rock and soils). Larger vegetation coverage than soil coverage is possible due to the canopy effect of the vegetation. Furthermore, we differentiated between the northwest and south exposed slopes, because according to Olsvig-Whittaker et al. (1983), an effect of solar radiation on soil moisture and vegetation and thus on evaporation can be expected on these slopes (Table 2).

3.2 Soil sampling and data analysis

To estimate SOC stocks, we took 82 soil samples covering all ecohydrologic units described above at the northeast and south-facing slopes. The number of samples per ecohydrologic unit was arranged to ensure a sufficient amount of samples for each set of relevant ecohydrologic surface properties along a slope (see Table 2). Soil sampling was conducted along a N–S transect through the studied valley at sampling sites across each ecohydrologic unit (see Fig. 1) in regular depth intervals (0–5, 5–15, 15–20 cm), continuing in

Table 1 Observed and mapped properties of the ecohydrologic units in the study area Sede Boker according to the findings of Olsvig-Whittaker et al. (1983), Schreiber et al. (1995), and Yair and Shachak (1982). Mean soil depth refers to areas covered by soil, and the rock/soil ratio is calculated as (100−soil cover)/soil cover

Ecohydrologic unit / general characteristics	Ecohydrologic unit	Mapped characteristics
Flat desert pavement (FDP) Uppermost unit with thinly bedded limestone and flint concretions Very shallow patchy soil and low vegetation coverage Dominant lithology: upper Netser formation		Slope: 6 % Soil cover: 30 % Soil depth: 15.76 cm Vegetation coverage: 10 % Rock/soil ratio: 2.33 pH (H_2O): 8.19 SOC_c (g 100 g^{-1}): 0.46 SIC (g 100 g^{-1}): 6.29
Gently sloped desert pavement (SDP) Forms the transition zone from the flat desert pavement to the incised valley Higher soil and vegetation coverage than FDP, accumulation of aeolian deposits Dominant lithology: upper Netser formation		Slope: 15 % Soil cover: 27.5 Soil depth: 18.75 cm Vegetation coverage: 22 % Rock/soil ratio: 2.63 pH (H_2O): 7.76 SOC_c (g 100 g^{-1}): 1.08 SIC (g 100 g^{-1}): 4.33
Stepped and fissured bedrock slope (FBS) Thinly bedded and densely fissured formation with stepped topography Soil accumulated in two different environments: (1) concentrated in crevices and fissures (2) accumulated in non-contiguous soil patches (Yair and Shachak 1982) Dominant lithology: lower Netser and upper Shivta formation		Slope: 20 % Soil cover: 45 % Soil depth: 20.52 cm Vegetation coverage: 32 % Rock/soil ratio: 1.22 pH (H_2O): 7.95 SOC_c (g 100 g^{-1}): 1.09 SIC (g 100 g^{-1}): 4.73

intervals of 20 cm where possible until the profile met bedrock). In addition to SOC concentrations, information of corresponding soil depth, bulk density, and coarse fraction are necessary to estimate SOC stocks (Eq. 1). Soil was sampled with a soil core sampler with a given volume (100 cm^3), which allowed the estimation of the soil bulk density BD (g cm^{-3}) based on the total soil weight (in grams) and the volume of the cylinder (in cubic centimeters) (Ravindranath and Ostwald 2008; Rodeghiero et al. 2009). The coarse fraction CF (g 100 g^{-1}) was calculated by the weight of coarse grains (>2 mm) divided by the total weight of the sample. At sampling sites with very shallow soils, such as weathering planes or depositional patches at the base of the steps, a mixed bag sample of 150 g was collected for a certain sampling area. In this case, the bulk density was estimated by multiplying the sampling area with the mean soil thickness of the sample.

3.3 Laboratory and statistical SOC analysis

Soil analysis was conducted in the laboratories of the University of Basel, Switzerland. The samples were

Table 1 (continued)

Ecohydrologic unit / general characteristics	Ecohydrologic unit	mapped characteristics
Non-fissured bedrock slope (BS) Extensive bedrock outcrops of massive limestone with low density of deep cracks Bedrock weathers into cobbles and boulders Soil shallowly accumulated as small soil patches Dominant lithology: upper Drorim formation		Slope: 21 % Soil cover: 7.5 % Soil depth: 10 cm Vegetation coverage: 9 % Rock/soil ratio: 12.33 pH (H_2O): 8.14
		SOC_c (g 100 g^{-1}): 0.61 SIC (g 100 g^{-1}): 4.37
Slope and valley colluvium (SVC) Soil bedding can be described as a colluvial mantle Densely jointed and covered with an colluvial mantle (Dan et al., 1972) Dominant lithology: lower Drorim formation		Slope: 18 % Soil cover: 45 % Soil depth: 28.66 cm Vegetation coverage: 23 % Rock/soil ratio: 1.22 pH (H_2O): 8.23 SOC_c (g 100 g^{-1}): 0.72 SIC (g 100 g^{-1}): 5.26

Table 2 Mean soil depth (related to soil-covered areas), median soil, and vegetation coverage and minimum, median, mean, max, and standard deviation of SOC stocks with respect to aspect and ecohydrologic units. The ecohydrological units in the table are ordered according to their sequence along the studied transect (compare Fig. 1). *N* northern aspect, *S* southern aspect, *FDP* flat desert pavement, *SDP* gently sloped desert pavement, *FBS* stepped and fissured bedrock slope, *BS* non-fissured bedrock slope, *SVC* slope and valley colluvium

Aspect	Ecohydrologic unit	No. of samples	Soil depth (cm)	Soil coverage (%)	Vegetation coverage (%)	$SOC_{stock,ehu}$ (kg C m^{-2})				
						Min	Median	Mean	Max	STD
N	FDP	9	15.3	30	10.5	0.13	0.26	0.28	0.74	0.18
N	SDP	23	12	40	21	0.06	0.56	0.72	1.90	0.55
N	FBS	7	17	45	35	0.68	1.21	1.42	3.04	0.78
N	BS	5	12	5	–	0.08	0.09	0.12	0.25	0.07
–	SVC	6	28.7	45	23	0.07	0.85	0.93	1.81	0.72
S	BS	8	14	10	–	0.03	0.07	0.07	0.13	0.04
S	FBS	14	19	45	12	0	0.59	0.71	2.37	0.63
S	SDP	3	23.1	15	5	0.02	0.22	0.17	0.26	0.13
S	FDP	7	24.7	30	–	0.05	0.15	0.21	0.39	0.13
	Total	82	18.7	29.4	24	0	0.31	0.58	3.03	0.61

initially dried at 40 °C and afterwards sieved using a stack of sieves to separate the coarse fraction (>2 mm), the fine fraction (<2 mm), and the fraction smaller than 0.032 mm. The latter was subject to further particle size analyses carried out with a SediGraph (SediGraph 5100, Micromeritics). That way, information about the clay fraction was obtained to test its influence on SOC stocks. SOC concentrations were measured using a LECO 100 CHN analyzer. First, total C content was measured with the untreated samples. Second, we estimated the SOC content based on the loss of ignition with 500 °C. Third, we calculated the soil inorganic carbon content for the same sample (without organic matter after burning) using again the CHN analyzer. For each representative layer i of a soil sample with thickness $d_{\mathrm{soil,\ i}}$ (in centimeters), SOC stock ($\mathrm{SOC}_{\mathrm{stock,\ i}}$, in kilograms of carbon per square meter) was estimated based on Eq. (2):

$$\mathrm{SOC}_{\mathrm{stock,\,i}} = 0.1 \times d_{\mathrm{soil,\,i}} \times \mathrm{BD} \times \mathrm{SOC}_{\mathrm{ci}} \times (1 - \mathrm{CF_i}/100) \quad (2)$$

SOC stocks ($\mathrm{SOC}_{\mathrm{stock}}$) per sampling site were then calculated by summarizing the SOC stock of each layer i at the corresponding sampling site:

$$\mathrm{SOC}_{\mathrm{stock}} = \sum \mathrm{SOC}_{\mathrm{stock,\,i}} \quad (3)$$

Based on Eq. (3), SOC stocks are not integrated over a certain reference depth, but for the entire soil column. To consider the limited soil coverage in each ecohydrological unit, we multiplied the stocks given in Eq. (3) with the mean soil coverage of each unit:

$$\mathrm{SOC}_{\mathrm{stock,\,ehu}} = \mathrm{SOC}_{\mathrm{stock}} \times \mathrm{soilcoverage} \quad (4)$$

To test the influence of the ecohydrologic units on SOC storage, the factors in the SOC-stock equation (Eq. (3) and the $\mathrm{SOC}_{\mathrm{stock,\ ehu}}$ (Eq. (4) estimates for each ecohydrologic unit were compared using box–whisker plots. The Kruskal–Wallis test was used to compare the variability of soil properties between ecohydrologic units with the variability within the units. The non-parametric Wilcoxon test for non-normally distributed variables was additionally used to test for differences of SOC stocks between pairs of ecohydrologic units. In the case of significant difference between the ecohydrological units (e.g., higher variability between the units than within the units), calculated p values are lower than 0.05 (equal to a level of significance of 5 %). For each ecohydrological unit, averages and standard deviation for each soil property were calculated. The spatial variations were evaluated by the coefficient of variation CV, which is given by the ratio of the standard deviation to the mean value of each soil property. The CV therefore allows the comparison of the variations of each soil property in different ecohydrologic units through the normalization of the standard deviation.

4 Results

4.1 Variability of SOC stocks and controlling soil properties

The results regarding the minima, mean, median, maxima, and standard deviations of the measured soil properties (BD, CF, $\mathrm{SOC_c}$, and d_{soil}) and the calculated SOC stocks are summarized in Tables 2 and 3. The largest variability of all SOC-stock controlling variables is displayed by the coarse fraction (CF factor in Eq. (1)), which ranges between 0 and 45.4 g 100 g^{-1} with a mean of 12.0 g 100 g^{-1} and a coefficient of variation of 81 %. $\mathrm{SOC_c}$ shows the second largest variability of the independent variables in Eq. (1), ranging from 0 to 4.48 g 100 g^{-1}, with a mean value of 0.86 g 100 g^{-1} and a coefficient of variation of 78.8 %. Soil depths range between 5 and 60 cm with a CV of 59.5 %. The lowest variability of the independent variables in Eq. (1) is shown by BD ranging between 0.56 and 1.90 g cm^{-3}, with a mean of 1.30 g cm^{-3} and a CV of only 20.7 % (see Table 3).

The large variability associated with the independent variables of BD, CF, $\mathrm{SOC_c}$, and d_{soil} is propagated through the calculation of the carbon stocks (Eqs. 1, 2, 3, and 4). Calculated SOC stocks show a wide variability ranging from 0 up to 3.03 kg C m^{-2}, with a mean of 0.58 kg C m^{-2} and a standard deviation of 0.61 kg C m^{-2}. The estimated CV of 105 %, which is the largest of the soil properties presented in Table 3, is mainly a result of the large spatial variability associated with the coarse fraction and the SOC concentration.

4.2 SOC stocks, soil properties, and ecohydrology

The median SOC concentration shows strong differences between the north- and the south-facing slopes (Fig. 3) and a tendency of increasing concentration downslope from the N-FDP to the N-FBS (Fig. 4a). As a combination of differences in aspect and the downslope increase, the greatest SOC concentrations are shown in the north-facing FBS (see Fig. 4q). Soil depths are higher on the S-facing slope and lowest on the N-facing slope (see Figs. 3c and 4b). Maximum soil depths and variability are observed in unit SVC, which is generally covered by a layer of colluvial deposits (up to 50 cm). Somewhat lower soil depths are observed at unit FDP of the northern exposed slope, while at the southern slope, this unit is characterized by higher values. As suggested by the Kruskal–Wallis test (p value= 0.19), differences of soil depth between ecohydrological units are not significant (see Fig. 4b). In contrast, significant

Table 3 Minima, median, mean, maxima, and standard deviation of measured soil properties relevant for the calculation of the SOC stock

Parameter	Min	Median	Mean	Max	STD	STD/mean (%)
BD (g cm^{-3})	0.56	1.30	1.30	1.90	0.27	20.7
CF (g 100 g^{-1})	0	10.38	12.02	45.42	9.74	81.0
SOC_c (g 100 g^{-1})	0	0.67	0.86	4.48	0.68	78.8
$SOC_{stock,\ ehu}$ (kg C m^{-2})	0	0.31	0.58	3.03	0.61	105.17
Soil depth (cm)	5	15	18.7	60	11.12	59.46

Values are calculated using the entire dataset (n=82). Mean soil depth refers to areas covered by soils. According to Eq. 4, SOC stocks refer to the entire area of the study site

differences of the $SOC_{stock,\ ehu}$ between the ecohydrologic units are confirmed by the p values derived from the Kruskal–Wallis test and the non-parametric Wilcoxon test (see Fig. 4c). The Wilcoxon test indicates that the EHUs cannot be stratified into clearly defined statistical groups according to their SOC stock. SOC stocks of the N-FBS unit are significantly higher than the other EHUs (expect for the SVC), but other EHUs do not classify into groups that are defined by major gaps of SOC stock in between. The trend along the transect (from N-FDP to S-FDP) is similar to the SOC concentration (see Fig. 4a) and dissimilar to the soil depths given in Fig. 4b. The mean vegetation coverage (see Fig. 4d and Table 2) is characterized by the largest differences between the aspect and the ecohydrologic units. The trend of the vegetation coverage along the different ecohydrologic units (see Fig. 4d) is similar to the trend of the SOC concentration and stock (see Fig. 4a, c). The lowest median vegetation coverage is observed at the southern SDP (5 %) and the highest median coverage at the northern exposed FBS (35 %) (see Fig. 4d and Table 2).

The clay fraction in all soil samples ranged from 9.05 to 16.61 %, with a mean of 13.23 % and a standard deviation of 2.32. No significant differences in average clay content between ecohydrologic units were identified, which suggests that clay content had only a minor effect on SOC stocks.

Measured SOC contents do not exhibit a notable vertical gradient at a point (Fig. 5). The SOC concentrations in the upper 40 cm of the soil are characterized by a strong variability, without any detectable trend. Below 40 cm, SOC concentrations are somewhat lower, with a smaller variability.

5 Discussion

5.1 SOC stock, surface characteristics, and vegetation

The very strong control of vegetation on the SOC concentration and $SOC_{stock,\ ehu}$ is revealed by their similar pattern on different aspects (see Fig. 3) and in the ecohydrologic units (see Fig. 4). Mean SOC concentrations and stocks strongly correlate with vegetation coverage in each ecohydrologic unit (R^2=0.8 and 0.9, respectively, Fig. 6a and b). The highest SOC concentration and $SOC_{stocks,\ ehu}$ are found at slope exposures that favor high soil moisture and thus

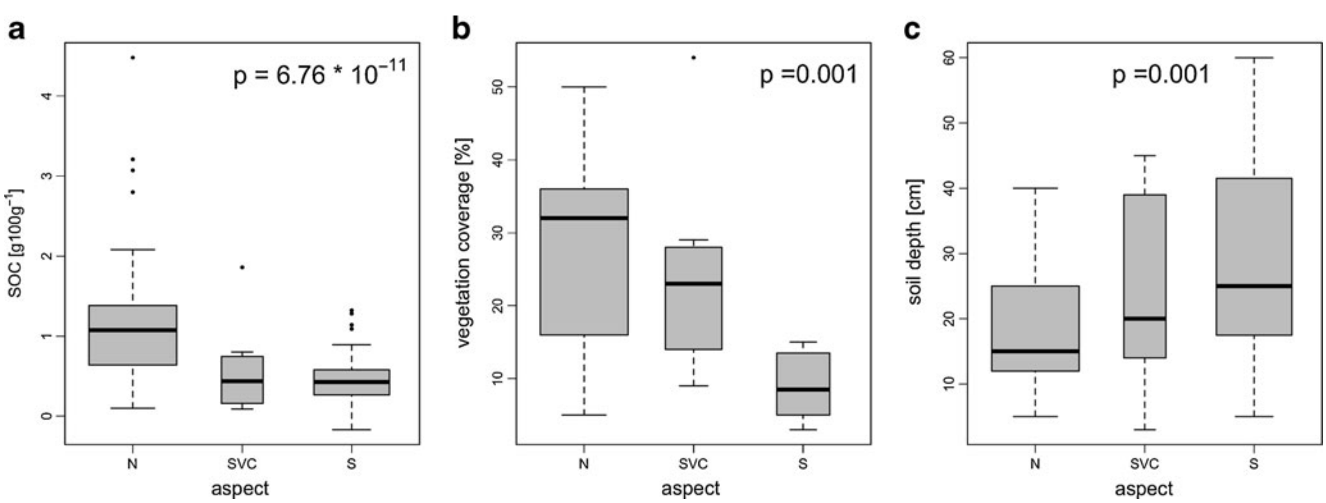


Fig. 3 SOC concentration (g 100 g^{-1}) (**a**), vegetation coverage (in percent) (**b**), and soil depth (in centimeters) (**c**) with respect to aspect from the whole investigation area. *N* and *S* indicated northern and southern aspects, respectively. The *boxes* have widths proportional to the number of sampling points in each box (number of total measurements, 82)

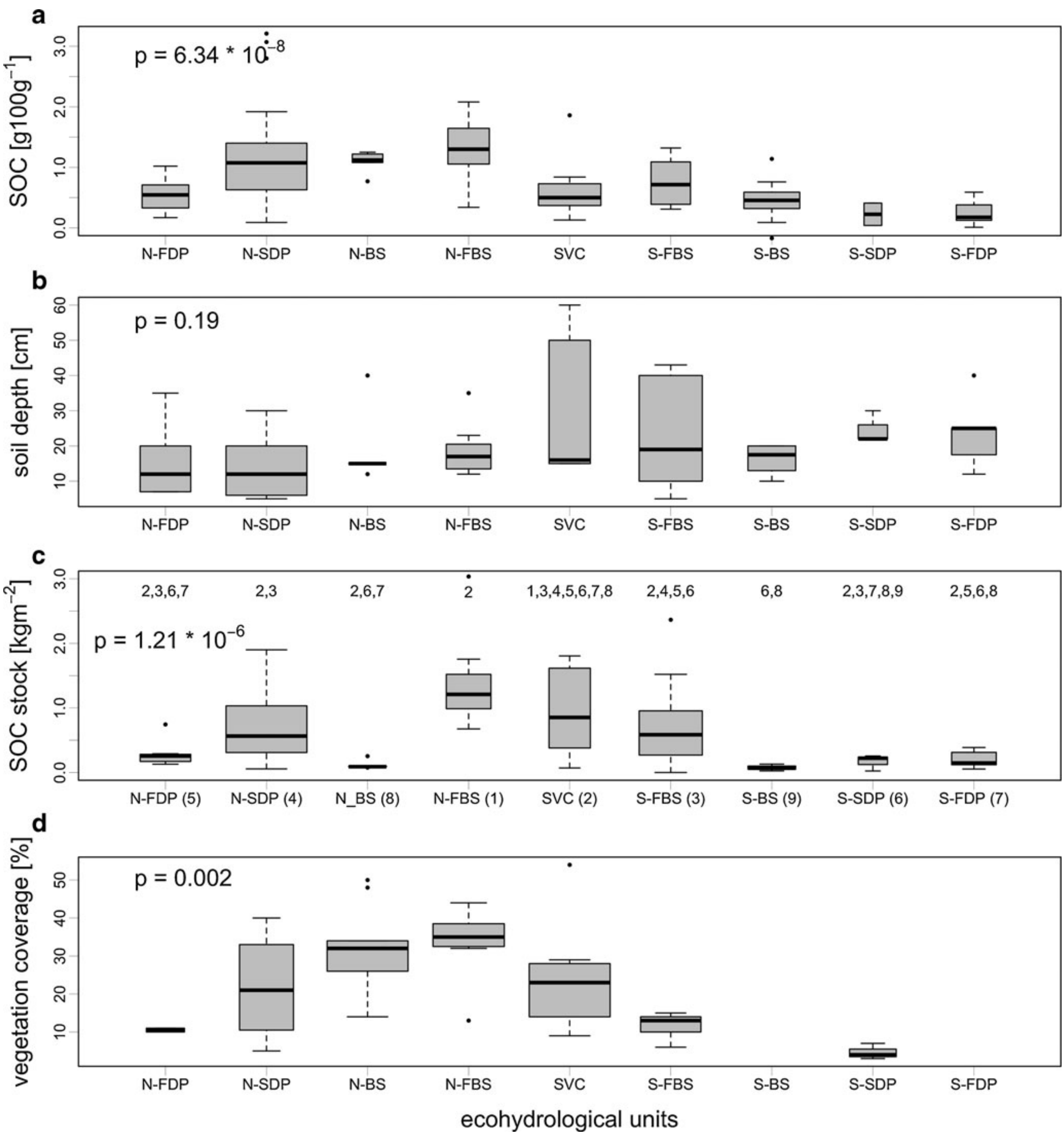


Fig. 4 **a** SOC concentration, **b** soil depths, **c** $SOC_{stock,\ ehu}$, and **d** vegetation coverage, **d** with respect to correspondence ecohydrologic unit and aspect. *N* and *S* indicated northern and southern aspect, respectively. *FDP* flat desert pavement with significant higher soil cover and depth due to minor slope gradient, *SDP* gently sloped desert pavement with lower soil depth due to higher slope gradient, *FBS* stepped and fissured bedrock slope, *BS* non-fissured bedrock slope, *SVC* slope and valley colluvium. Ecohydrologic units are ordered in correspondence to their locations from N to S along the transect. The *numbers* in brackets following the EHU names of Fig. 4c denote the rank of the EHU (e.g., the highest median of N-FBS is given by *(1)*, the lowest for S-BS given by *(9)*). The *numbers* above the *boxes* denote EHUs (according to their rank) with a similar SOC-stock distribution (as given by $p>0.05$ using the non-parametric Wilcoxon test). The *boxes* have widths proportional to the number of sampling points in each box (number of total measurements, 82). The *p* values are derived using the Kruskal–Wallis test and give significant differences between EHUs in case $p<0.05$

high vegetation densities (e.g., northern exposed slopes and lower slope positions, Figs. 3 and 4). In contrast, the mean soil depth of the ecohydrologic units correlates only very weakly with SOC concentration (see Fig. 6c), and no correlation is found between soil depth and $SOC_{stock,\ ehu}$ (see Fig. 6d). Thus, aspect-driven microclimatic effects that control soil moisture and vegetation coverage appear to affect SOC stocks more strongly than soil depth. The lacking relevance of soil thickness on rocky desert slopes is in strong contrast to its importance for SOC stocks in more humid areas (Berhe et al. 2008; Yoo et al. 2006). The positive relationship between vegetation coverage and SOC stocks at Sede Boker shows that the findings of Olsvig-Whittaker et al. (1983), who studied the effects of surface properties on vegetation, can also be applied to SOC stocks. Our results suggest that the different ecohydrologic conditions along rocky desert slopes near Sede Boker identified by Olsvig-Whittaker et al. (1983), Schreiber et al.

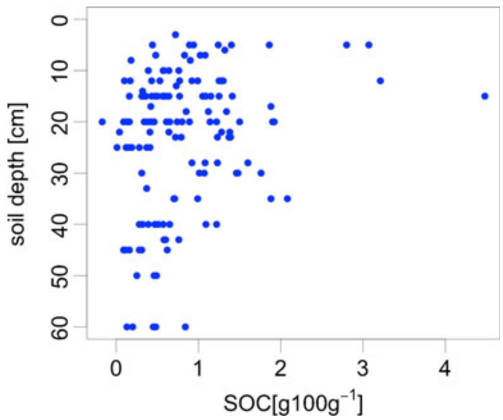


Fig. 5 SOC concentration as a function of depth below surface, plotted for every sample (n=82)

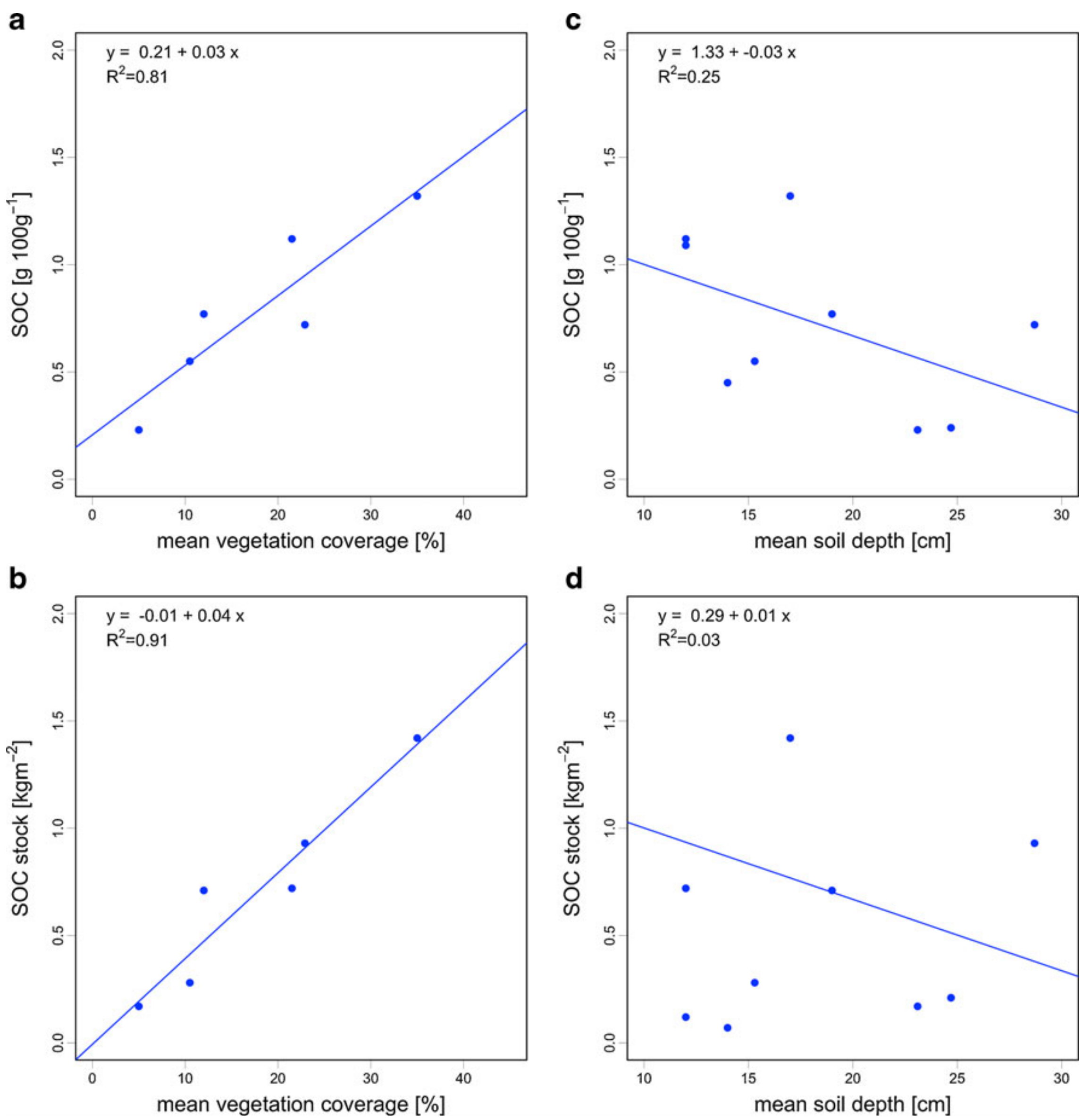


Fig. 6 Scatterplot of SOC concentration (**a**, **c**) and $SOC_{stock,\ ehu}$ (**b**, **d**) of sampled soils versus vegetation coverage and soil depth. Values are mean values obtained for each ecohydrologic unit

(1995), and Yair and Raz-Yassif (2004) also affect the SOC stocks on the different units. A similar effect is reported by Li et al. (2010) and Jobbágy and Jackson (2000) who both found a strong link between aboveground vegetation properties (e.g., density, type, stand age) and SOC. Our results also suggest that vegetation coverage provides a direct index for the spatial pattern of SOC stocks in drylands.

5.2 Surface processes and SOC stocks

The variability of the soil properties and the SOC stocks at Sede Boker is associated with differences in slope aspect (see Fig. 3) and NPP of the ecohydrologic units along the rocky desert slopes (see Fig. 4, Tables 2 and 3). In accordance with Olsvig-Whittaker et al. (1983), these results imply a positive dependency of SOC stocks on the relative moisture supply, which is given by surface runoff and aspect-driven differences of evaporation. The discontinuity of runoff associated with the patchwork of water sources and sinks also affects the distribution of SOC in the soil profile. In undisturbed soils, a strong vertical SOC gradient between topsoil and bottom soil is common (Arrouays and Pelissier 1994; Mishra et al. 2009; Wang et al. 2004). At Sede Boker, fine sediments provide the bulk substrate for soil formation and are preferentially deposited in small depressions and bedrock fissures, which act as local sediment sinks (see Figs. 1 and 2) (Olsvig-Whittaker et al. 1983; Yair and Danin 1980). Soil depth therefore varies on a centimeter to meter scale due to the spatial pattern of bedrock surface morphology. Eroded topsoils, which are generally enriched in SOC, are deposited in these fissures and may be stored over a long period of time. The limited change of SOC concentration with depth (see Fig. 5) at our sampling sites is in agreement with strong SOC redistribution and deposition at Sede Boker. Thus, the relationship of SOC content and soil depth appears to be strongly influenced by lateral soil movement, highlighting the need to consider soil as a mobile layer, formed by selective erosion and deposition (Hoffmann et al. 2009; Kuhn et al. 2009), which varies in time through changing source areas and/or the changing soil conditions in the source area (Dotterweich 2008).

5.3 SOC-stock comparison with other drylands

Table 4 summarizes results of SOC studies in arid and semi-arid areas, regarding the measured SOC concentrations and stocks. The estimated $SOC_{stocks,\ ehu}$ of the Sede Boker study area are in a similar range, while SOC concentrations are generally greater than those in other arid environments (see Table 4). Because $SOC_{stocks,\ ehu}$ refer to the entire study site and SOC concentrations to places in which soils are developed, the similar spatial pattern of $SOC_{stocks,\ ehu}$ and

Table 4 Global comparison of SOC and SOC stocks in different arid environments

Reference	Region	Environment	MAP (mm $year^{-1}$)	Area (km^2)	Reference depth (cm)	SOC stock (kg C m^{-2})	SOC_c (g 100 g^{-1})
Schlesinger (1977)	Global	World desert soils		1.83×10^9	Not specified	0.023–0.055	
Amundson (2001)	Global	Warm desert		14×10^6	Not specified	1.4	
Watson et al. (2000)	Global	Deserts and semi-deserts		45.5×10^6	0–100	4.37	
Feng et al. (2002)	Land regions of China	Different desert types	46–800	Variable	0–100	0.02–12.52 (mean, 2.32)	
Feng et al. (2002)	Land regions of China	Different desert types	46–800	Variable	0–20	0.02–4.97 (mean, 1.12)	
Balpande et al. (1996)	Central India	Vertisols	877–975	Profile measurement	Not specified		0.1–0.4
Zak et al. (1994)	Mexico, S-USA	Chihuahuan desert	240	Point measurement	Not specified		0.16
Bolton et al. (1993)	SE Washington, USA	Sagebrush steppe	100–250	Point measurement	Not specified		0.08
Perkins and Thomas (1993)	Kalahari, Botswana	Kalahari desert	150–600	Point measurement	Not specified		0.2–0.6
Ardö (2003)	Sudan	Semi-arid Sudan	200–800	2.62×10^6	0–20	0.06	
Zaady et al. (1996)	Negev, Isreal	Negev desert	200	Point measurement	Not specified		0.45–0.56
Fliessbach et al. (1994)	Negev, Israel	Negev desert	90 (19.5–180)	Point measurement	Not specified		0.03
This study	Sede Boker Negev, Israel	Rocky desert	91 (34–167)	0.045	Variable	0.31 (0.0–3.03)	0.67 (0.0–4.48)

MAP mean annual precipitation

increased SOC concentrations are attributed to the patchiness of soil cover in our study area compared to other areas cited in Table 4. While large fractions of our study area have rocky surfaces, sites with soil cover also carry vegetation and thus increased SOC concentrations. This is in accordance to the "islands of fertility" (Schlesinger and Pilmanis 1998) with increased biogeochemical processes, NPP, and SOC concentrations. Furthermore, higher concentrations in our study site might be attributed to the reduced mineralization of SOC, due to the lack of water in the Negev desert (Yao et al. 2010) and/or the degradation of soil due to overgrazing (compare for instance Bolton et al. 1993) in some of the other sites mentioned in Table 4. The comparison of our study to those presented in Table 4 remains limited. The studies presented in Table 4 rely on different measurement techniques of the SOC, different upscaling approaches, and variable reference soil depths taken into account. Unfortunately, reference soil depths are only given for 4 of the 13 case studies. Differences in SOC stocks may thus not represent environmental conditions, but simply the different methodologies applied for inventorying. The comparison indicates that the number of high-resolution SOC inventories in arid environments is very limited, and more case studies using a comparable methodology are necessary to evaluate the importance and potential changes of SOC in arid environments. In any case, on a global scale, the relatively large $SOC_{stocks,\ ehu}$ in our study area indicates that soils in arid environments, especially in rocky deserts associated with hardly any soil cover, may comprise a significant SOC pool that is sensitive to NPP. Even the admittedly somewhat arbitrarily calculated average soil depth of 18 cm is also in contrast to the notion that rocky deserts do not contain significant soil cover and thus SOC.

6 Conclusions

This study aimed at identifying the relationship between surface characteristics, vegetation coverage, and SOC concentration and stocks in the arid northern Negev in Israel. Soils cover 30 % of the study area, and the soil-covered areas are on average 18 cm deep and contained similar concentrations of SOC than soils from more humid drylands. However, the results show a large spatial variability of SOC, soil bulk density, and soil thickness. Consequently, the estimated SOC stock ranges between 0 and 3.03 kg C m^{-2} with a mean of 0.58 kg C m^{-2} (median, 0.31 kg C m^{-2}) and a standard deviation of 0.61 kg C m^{-2}. The differences in SOC stocks between ecohydrologic units on the north- and south-facing slopes indicate the relevance of eco-climate and thus the potential impact of climate change on rocky desert SOC stocks. They confirm that conceptual approaches, which explain the spatial patterns of vegetation cover on rocky desert slopes in the Negev, can also be applied to SOC stocks. In addition to climate-driven differences between aspect and slope position, the ecohydrologic units take changes of small-scale surface properties into account. The small-scale variability is mainly caused by lithology-driven differences of the microtopography, which provides accommodation space in fissures and on bedrock steps, for fine sediment accumulation and soil formation. Thus, significant differences of SOC stocks as well as vegetation densities between ecohydrologic units demonstrate that small-scale surface properties modulate climate-driven differences and provide a further control on the presence or absence of soils and thus on the amount of SOC storage.

In more general terms, our results show that dryland soils contain a significant amount of SOC even in arid regions. Even this amount is smaller than in more humid environments; it is of major importance for the functioning and thus conservation of arid ecosystem. Differences in eco-climate, microtopography, surface processes, soil formation and properties, and vegetation between the ecohydrologic units are apparently of greatest importance for SOC stocks in drylands. The results strongly suggest that the microscale (decimeter to meter) water supply and NPP, as indicated by the vegetation coverage, determine SOC stocks on rocky desert slopes. The variability of SOC stocks, driven by aspect, soil moisture availability, and vegetation coverage, also implies that SOC stocks in arid environments are highly sensitive to climate change and thus represent a major unstable C pool within the global carbon cycle of the twenty-first century.

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